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Analysis of velocity profiles from wind tunnel experiments with saltation

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Introduction

In the past two decades, increasing effort has been directed at probing and modeling the internal dynamics of saltation layers. Wind tunnels have proven indispensable in this regard, especially for testing the legitimacy of various ideas about sediment-fluid interaction under tightly controlled experimental conditions. Unfortunately, it is not always apparent how to analyze and interpret even relatively simple measurements such as the vertical profile of time-averaged wind speed. Complete descriptions of the mean streamwise velocity distribution, U(z), in a turbulent boundary layer are generally derived by a classical asymptotic matching procedure that requires the inner layer profile (Law of the Wall) to be matched to the outer layer profile (Velocity Defect Law) in an overlap region or 'inertial sublayer' (Raupach et al., 1991), which leads to the well-known logarithmic law,

$$\frac{U(z)}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z\,u_*}{\nu}\right) + B \qquad \text{Equation (1)}$$

where u_* is shear (or friction) velocity, κ is the von Karman constant (taken as 0.41), z is height above the bed, ν is kinematic viscosity, and B is an integration constant that depends on surface roughness and shear velocity. In most earth science applications, the logarithmic law takes an alternative, more general form that employs z_o, the roughness length or height above the bed at which flow velocity tends to zero.

In many natural systems (and evidently also in wind tunnels), the flow in the outer region of the boundary layer deviates progressively from the linear Velocity Defect Law. In order to account for this deviation, Coles (1956) proposed the Law of the Wake, which can be manipulated to yield a velocity-defect form:

$$\frac{U_\infty - U(z)}{u_*} = \frac{1}{\kappa}\left[-\ln\left(\frac{z}{\delta}\right) + 2\Pi + 2\Pi \sin^2\left(\frac{\pi}{2}\frac{z}{\delta}\right)\right] \qquad \text{Equation (2)}$$

where U_∞ is free stream velocity, δ is boundary layer depth, and Π is a profile parameter that depends on the distribution of stress in the boundary layer. This expression applies to the entire boundary layer above $zu_*/\nu=30$ presuming that Π is constant (Spies et al., 1995). A value of $\Pi=0.55$ for clean air flows has been widely adopted, but Spies et al. (1995) suggest that a value of $\Pi=0.6$ may be more appropriate when aeolian sand transport is active.

It is widely appreciated that the presence of moving sediment in the near-surface region of the boundary layer alters the fluid dynamics of the inner layer. Nevertheless, the logarithmic law continues to be applied widely, either in the form of the equations presented above or those proposed by Bagnold or Owen, which were derived specifically for aeolian saltation systems. The challenge facing the aeolian geomorphologist, and the subject of this paper, is to determine which of these many alternative expressions provides the most realistic and complete description of a measured velocity profile whether from the field or wind tunnel.

Methods

A series of runs was conducted in the University of Guelph recirculating wind tunnel with fine-grained (D_{50} = 0.19 mm) and coarse-grained (D_{50} = 0.25 mm) quartz sand. For each run, the sand bed was flattened by running a straight-edged bar along the tops of two metal side rails fixed to either side of the tunnel. The fan motor was set to a constant frequency, the sediment-feed system was then set to a supply rate that was sufficient to preclude sediment build-up or erosion beneath the hopper, and the transport system was given ample time for an equilibrium surface to establish itself (with low-amplitude ripples in most cases). Sediment transport rate was measured continuously using a wedge-type trap and high-precision electronic balance connected to a computer-controlled data-acquisition system.

Wind speed was measured using a high-speed thermal anemometry system (TSI 300) and a stainless-steel hot-film probe (TSI Model 1266). The probe was fixed to a precision rack-and-pinion mount that was located in the center of the tunnel immediately in front of the wedge trap. The probe was lowered toward the sand surface and then raised back up to the free-stream core by reversing the steps. After a vertical wind-speed profile was measured in its entirety, the fan and sediment-feed systems were turned off, the wind tunnel windows were opened, the entire sand surface was sprayed with water mist to 'fix' the surface, and an identical experiment was conducted on the stationary surface, absent sediment transport. Such paired runs were conducted across a range of free-stream velocities for both the fine-grained and coarse-grained sediment mixtures, yielding a total of 28 runs.

Results

Figure 1 shows several representative velocity profiles, with and without saltation, for the fine-grained and coarse-grained cases. Several features of these profiles are noteworthy. The uppermost portions of all the profiles show a pronounced deviation from the expected log-linear trend. This is believed to be an artifact of the constrained dimensions of the wind tunnel rather than a velocity-defect phenomenon as envisioned by Coles. Detailed inspection of the wind-speed time series showed that the turbulent signatures in these upper locations were distinctly different from those lower in the profile, and on this basis, the boundary-layer depth was assessed at 0.24 m for virtually all runs. The middle sections of the profiles (roughly between 0.06 m and 0.18 m) are consistently log-linear even when saltation was active. However, the slopes of the profiles are considerably different between the no-transport and with-saltation cases, especially as free stream velocity increases. Shear velocities derived from log-linear regressions through these middle sections are consistently greater for the with-saltation case in any given profile pair, reaffirming that the presence of the saltation layer does indeed have the effect of contributing an enhanced roughness to which the overlying wind field must adapt. Interestingly, these with-saltation regression lines appear to converge roughly near Bagnold's focal point (i.e., at a the height of ~ 0.003 m and an average wind speed of ~ 2.5 ms^{-1}). Nevertheless, such 'focusing' of the profiles never truly occurs because the lowermost portions of the profiles (less than ~ 0.05 m) begin to deviate significantly from the log-linear trend of the middle profile section. This is most evident in the high-speed profiles and especially when the saltation layer is well-developed. Shear velocities derived from the near-surface section of the profile are invariably smaller than those derived from the middle section. The question arises as to which is the most robust shear velocity estimate to use in transport modeling.

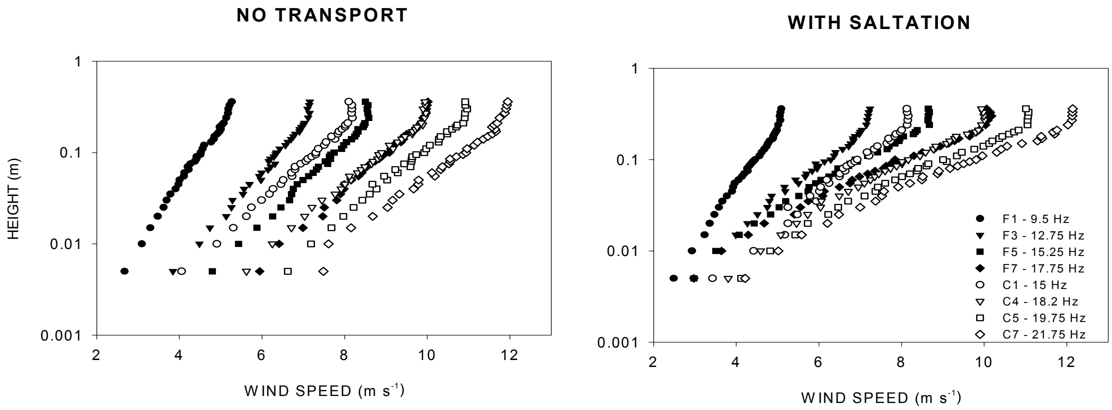

Figure 1. Representative wind-speed profiles with and without saltation for fine-grained (solid symbols) and coarse-grained (open symbols) sand. 'Hz' refers to fan speed.

A series of tests was conducted to fit six alternative velocity profile parameterizations to the data in order to determine what the implications might be for estimates of shear velocity and roughness length. Figure 2 shows the results of the shear velocity analysis for the fine-grained case only. Using a constant value of $\Pi=0.55$ in Equation (2) yields suspiciously small values for shear velocity, and this is exacerbated if a larger constant value for Π is employed. When the value of Π is derived independently from an analysis of the innermost profile segment and then applied to the outer flow region, realistic values of shear velocity are produced. These are surprisingly similar to the shear velocity estimates derived from a simple regression through only the innermost measurements (< 0.045 m). Shear velocity estimates based on two versions of the logarithmic law (e.g., Equation (1)) are similar to each other, and when there is no transport, these estimates are virtually the same as those using Equation (2). However, when there is active transport, these methods produce diverging estimates for shear velocity. A simple regression applied to the middle segment of the profile (between 0.06m and 0.18 m) produces unrealistically large estimates of shear velocity when there is a well developed saltation layer.

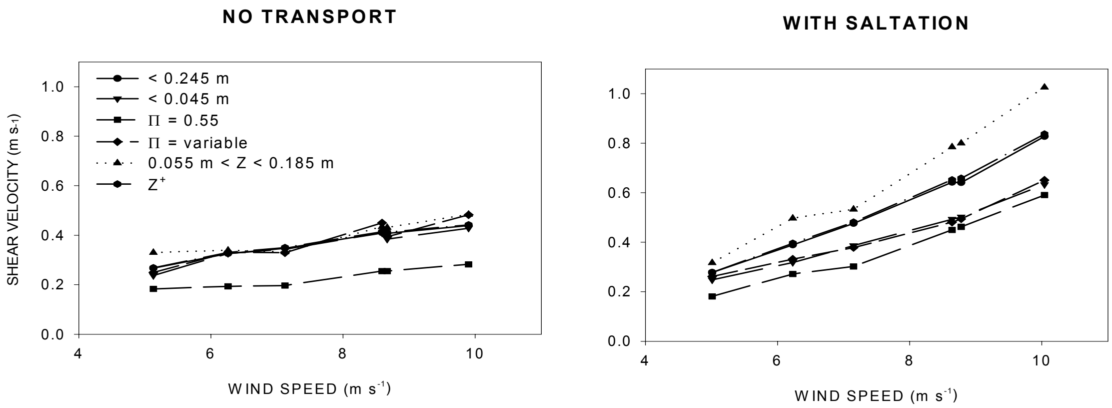

Figure 2. Shear velocity estimates from six alternative velocity-profile parameterizations for the fine sand case only.

Conclusions

Detailed analysis of wind-speed profiles from a series of wind-tunnel experiments shows that estimates of shear velocity can vary by almost two-fold depending on which profile parameterization is adopted. The prospects for sediment-transport prediction are therefore not encouraging. Employing a constant value of Π=0.55 (or greater) in Coles' Law of the Wake is not recommended. Calculating Π based on near-surface measurements is preferred, but this is time-consuming and requires very closely-spaced velocity measurements within the saltation layer—this is unlikely in field experiments. Restricting attention only to the boundary-layer segment immediately above the saltation layer, as is conventionally done, appears to produce over-estimates of shear velocity. Using wind-speed information from the entire boundary layer appears to provide the most robust estimates of shear velocity, although it is not known how these relate to sediment flux.

References

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